Development and application of computed tomography in the inspection of reinforced concrete

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This paper describes the development and application of reinforced concrete tomography, a non-destructive technique based on the use of gamma radiation for achieving 3D reconstruction of reinforcing bars and detecting corrosion in rebars and honeycombing in concrete. This novel method has already found a wide range of practical applications in inspections of well over a thousand structural elements in buildings, bridges, under-water pillars, oil-filled ducts, statues, bank treasuries and tunnels. This paper describes the technique, including the recently developed real-time tomograph, and presents illustrative examples of results achieved with it.

1. Introduction

Steel-reinforced concrete has been in use for well over a hundred years and this fact has led to the present-day reliance on this material for a large portion of our infrastructure in terms of buildings, bridges, roads, tunnels, dams, ducts, piers, etc. The reliability and safety of these structures have become an important factor in the standard of living and in the economic development worldwide and there are still problems that need to be investigated. Examples of such problems are the corrosion of reinforcing bars (rebars) in ageing structures or in structures where good construction practices were not followed; and the practice of 'recycling' buildings for new applications, often with increased loads and without the benefit of adequate documentation. Additionally, inadequate inspection during construction and non-adherence to construction codes are universal problems.

For these reasons, inspection of the existing reinforcement in concrete structures is an essential activity for their maintenance and possible modifications. By far the most prevalent inspection method is through destructive techniques. Jackhammers, pickaxes and chisels are used here and there to uncover and inspect a few rebars. The obvious drawbacks are a usually very limited scope of the inspection, the need to repair the damage, the noise dust and residues generated and the fact that often structures such as balconies are weakened beyond repair and need to be totally replaced. In addition, irreparable damage can be caused in the inspection of statues and ornaments of artistic value.

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As an alternative, THASA has developed, improved beyond the previous state-of-the-art, and applied over a decade, Reinforced Concrete Tomography (RCT), a non-destructive inspection technique of the highest precision, based on the use of gamma-rays. This technique has found a wide range of practical applications in buildings, bridges, under-water pillars, oil-filled ducts, statues and tunnels involving well over a thousand inspected structural elements.

Beneficiaries of this technology are primarily civil engineers who are responsible for issuing technical reports on the condition of structures and need data to base their reports on. Port, highway and railway authorities rely on this technology to meet maintenance requirements. Construction companies interested in quality controlling the work of subcontractors, insurance companies and landowners are also beneficiaries of this technology. The ultimate beneficiary is the general public, through safety improvements of buildings and other structures, and also through less disruption, no noise and absolute cleanliness during the inspection procedures.

An important initial motivation for the development of RCT was a tragedy that took place in 1992 at a beach resort on the Atlantic shore, 250 miles south of Buenos Aires. Four young people were killed when a balcony in a high-rise building where they were standing broke off. The ensuing investigation showed that just about every kind of malpractice was present: insufficient number of rebars of appropriate size, severe corrosion due to chlorine in the unwashed sand from the beach used in the construction of these balconies and steel bars placed too low. It was disturbing that there was no technical solution to detect these defects in balconies. RCT now provides the most complete answer to these kinds of problems.

2. Description of the technology

RCT is similar to computed tomography in the medical field. Gamma rays from a radioactive source illuminate the structure to be examined, and the transmitted beam is registered on photographic plates or by special detector-spectrometers.

The use of gamma rays for examining concrete samples in the laboratory was first reported by L Mullins and H M Pearson[1] and the possibility of extracting 3-D information of reinforcement was pointed out by A C Whiffin[2]. There are also standards for 'Gamma Radiography of Concrete'[3] and papers and references dealing with the use of electromagnetic radiation in general (conventional X-rays, gamma rays from radioactive sources, radiation from electron accelerators) to examine concrete. However, the systematic commercial application of RCT to other than laboratory testing in the civil engineering field is a new development.

The tomography or three-dimensional reconstruction of the reinforcement is achieved by using hardware designed to obtain the data in the field with the highest precision and software to analyse them. Software has also been developed to extract quantitative information on honeycombing (voids in concrete) and corrosion. The 'product' is a detailed technical report describing the work done and the results obtained for each beam, column or slab sector

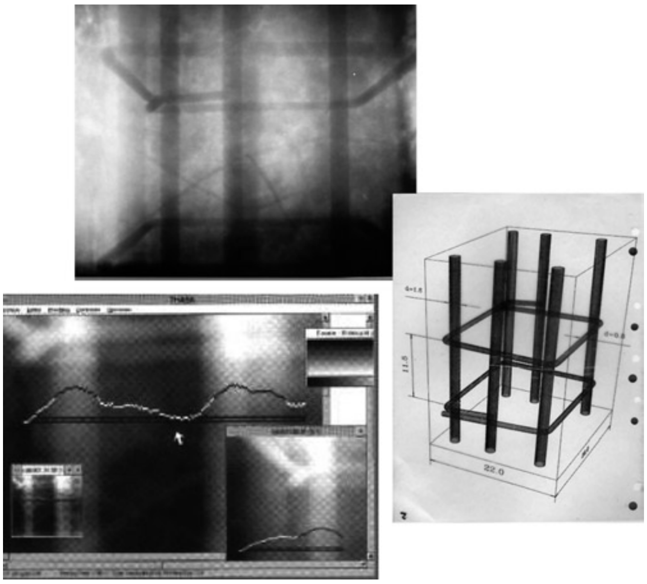

Figure 1. Gammagraphy of a column with six 16 mm ϕ rebars and stirrups obtained with a Cs137 source; digitised portion of it and 3D reconstruction

examined. The results include position, diameter and condition of steel bars, and indication of observed stirrups and presence of voids, cracks and any other element of interest to the customer.

Figure 1 shows a gammagraphy of a column, a digitised portion of it and the resulting 3D reconstruction. The column has six, 16 mm ϕ steel bars, three near the face close to the gammagraphic plate and three on the opposite side (the source side). The relative vicinity between the nearly-point source and the column yields an image with a marked perspective. The steel bars on the 'source side' project a wider shadow than those on the 'plate side'. This effect is readily seen in the case of the stirrups. The gammagraphy also shows details such as the presence of thin wires left inside the form.

Gammagraphies are also useful to show honeycombing (Figure 2) and rebar corrosion (Figure 3).

The honeycombing in Figure 2 corresponds to an inclined column of an inhabited apartment building showing important cracks on the outside. This gammagraphy helped to uncover this important deficiency with a minimum of disturbance as shown in Figure 4.

Figure 2. Evidence of honeycombing in an inclined column (corresponding to study shown in Figure 4). Obtained with an Ir192 source

RCT with gamma rays is superior to other non-destructive methods due to its (a) precision (1/32" for diameters, 3/8" for positions) and (b) completeness. Only with this method it is possible to determine all rebars in a complex structural element such as that shown in Figure 5, showing the results for a 27" wide beam with 34 rebars.

THASA owns an Argentine and US patent[4] which introduces the concept of using the penumbra to solve the problem of finding the size and position of a rebar out of one single gammagraphy (one orientation of the source) instead of two as in the conventional method. This is possible because the penumbra (which is caused by the finite extension of the source) is only a function of the position of the object along an axis perpendicular to the plate. A least-squares fit of the proper mathematical expression to the data corresponding to the shadow plus penumbra due to a rebar yields the values of its diameter and position.

Figure 3. Portion of a gammagraphy showing corrosion in a rebar, obtained with an Ir192 source

THASA has also carried out research on the use of gamma ray spectrometers, instead of gammagraphic plates, to achieve a real-time tool for concrete structure testing and other applications. The use of a spectrometer

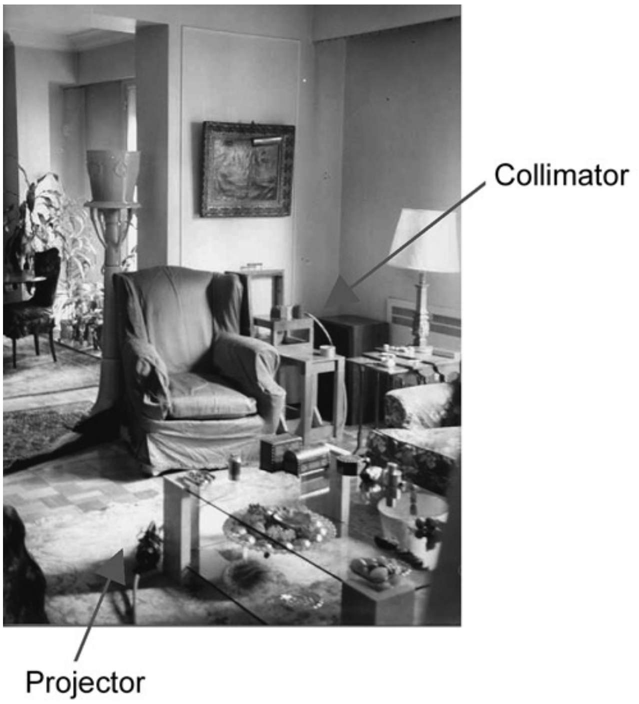

Figure 4. Example of 'field work' in an inhabited apartment showing how little disturbance is produced by RCT. The lower arrow points to the projector on the floor next to the coffee table. The upper arrow indicates the collimator housing the source during irradiation. This study uncovered the honeycombing defect shown in Figure 2

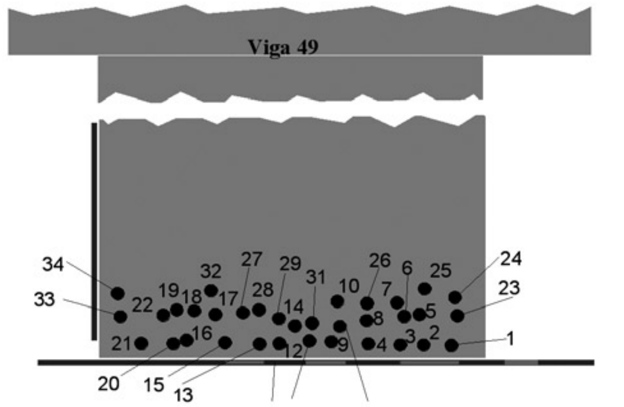

Figure 5. Tomographic results for the case of a 27" thick beam with 34 rebars

(a detector capable of discriminating among different gamma ray energies) has the advantage that unwanted scattered radiation can be filtered out electronically, thus improving contrast.

The early work dealt with the properties of a gammametric system and was carried out in collaboration with students at the University of Buenos Aires[5]. More recently a digital tomograph was built[6] based on CdTe and BGO detectors. Results corresponding to a beam are shown in Figure 6. Digital tomography is also useful to make quantitative determination of honeycombing not only on the plane perpendicular to the radiation but also on the plane parallel to it. Figure 7 compares a gammagraphy of a simulated honeycombing using an empty Coca-Cola bottle inside a concrete block with the results obtained with the digital tomograph, on the plane perpendicular to radiation. For the projection on this plane the gammagraphy is superior in space resolution to the digital output. However, from the digital measurement it is possible to extract precise determination of the honeycombing in the parallel direction (Figure 8).

3. Results

The first service contract applying RCT was a study of a historical building in the Buenos Aires harbour, the Argentine Yacht Club. The structure of this building was showing serious cracks and the main tower was dangerously tilted. The RCT work made it possible to find the causes of these problems and fix them. It also provided tomographies of one of the earliest implementations of reinforced concrete in Argentine (from 1910s), revealing gross misplacement of rebars and fancy stirrup layouts.

More than one hundred service contracts have been undertaken by THASA since then. They include the National Senate, the Buenos Aires-La Plata highway, many private apartment buildings, industrial plants, the Supreme Court Palace, the Luján Cathedral, underwater studies of Ushuaia harbor pillars, the Zarate Brazo Largo Bridge Complex, etc. (Figure 9). In all cases these studies contributed either to diminish risks and accidents or to obtain significant economic benefits. One example of the latter case is a bridge in the Republic of Uruguay that needed additional lateral strength. This was achieved by placing 24 transverse rods along the bridge through the four main beams. RCT was used to determine best spots for drilling holes without touching reinforcing bars, saving a lot of money in the process.

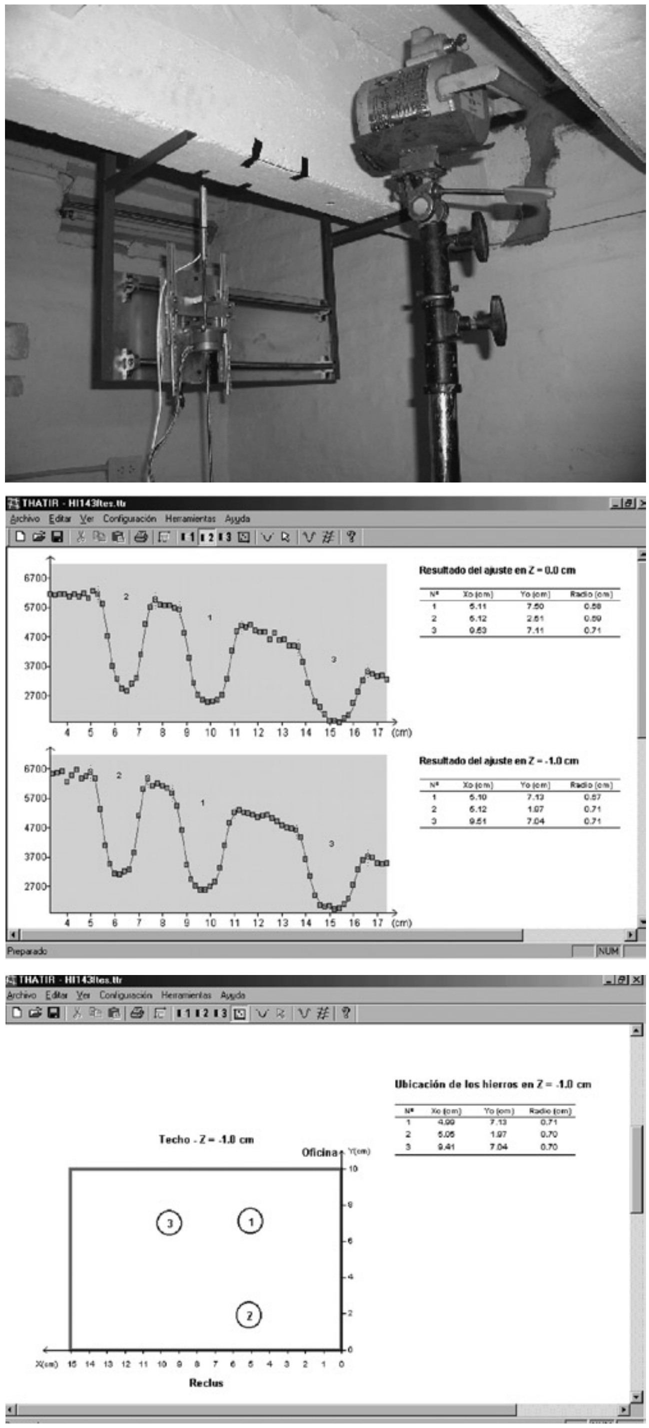

Figure 6. Digital-real time tomography. The upper picture shows the source-detector arrangement in the study of a beam. The plots below show the gamma intensity data for two sections as a function of the coordinate perpendicular to the main rebars. The curves in the middle frame are the best least squares fit to the data. The bottom frame shows the results

4. Summary

Reinforced concrete tomography has proved to be a useful, practical and economical non-destructive technique of wide application in the civil engineering field. In particular, it solves one problem for which there is no alternative, that of knowing the full configuration of reinforcement in complicated structures such as thick beams, slabs, balconies and similar structures. It is also valuable for determining honeycombing and corrosion and finding optimum locations for drilling in concrete with a high density of steel is required. Finally, RCT is a very practical instrument of quality control during construction of new buildings and in old ones subject to commercial transactions or insurance coverage.

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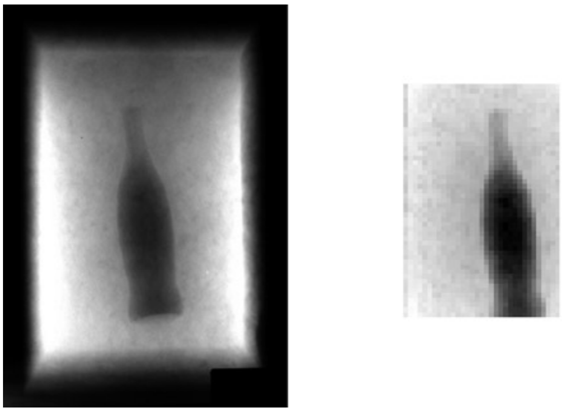

Gammagraphy **Digital image**

Figure 7. Comparison of a gammagraphy and a digital image of a Coca-Cola bottle placed inside a concrete block to simulate 'honeycombing' of known geometry. In both cases an Ir192 source was used

References

1. The X-Ray Examination of Concrete, L Mullins and H M Pearson, Civil Engineering and Public Works Review (London) 1949.
2. Locating Steel Reinforcing Bars in Concrete Slab, A C Whiffin, The Engineer (London) 1954.
3. Gamma Radiography of concrete, British Standards Institution (London) 1970.
4. Process for Determining the Internal Three-Dimensional Structure of a Body opaque to Visible Light by Means of Radiations from a Single Source, Specially suitable for Reinforced Concrete Parts., US Patent 5,828,723 Oct. 27, 1998 and Argentine Patent 252,846 Nov. 30, 1998.
5. The Application of Gammametry to the Study of Reinforced Concrete, A Ansaldi, J Contín, V Fierro, M A Tichno,

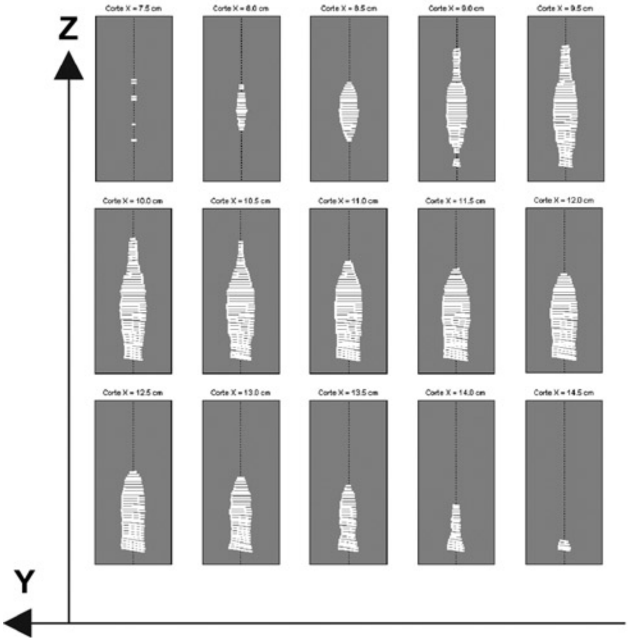

Figure 8. Air length equivalent in the plane parallel to radiation, for different values of the coordinate perpendicular to radiation. Unlike gammagraphy, a single scan provides a measure of the amount of air along each gamma ray path. In the case shown here it has been assumed that the amount of air along each gamma ray path is uniformly distributed around the centre of the block

A Distéfano and M A J Mariscotti, Nuclear Instruments and Methods in Physics Research B73(1993)531

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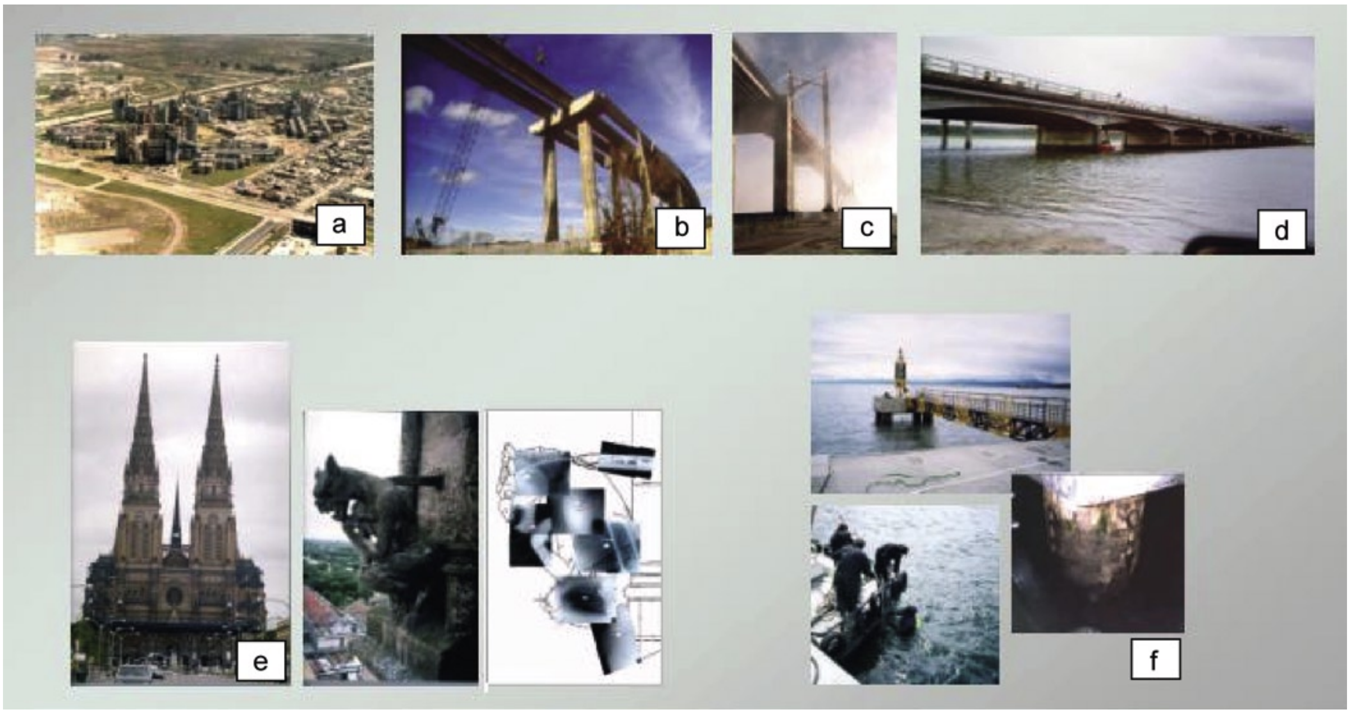

Figure 9. Illustrative examples of RCT services. (a) Housing development, studies of beams and slabs for the purpose of maintenance; (b) Buenos Aires-La Plata Hwy, quality control of beams; (c) Zarate Brazo Largo bridge complex, finding of voids in pre-stressed beam ducts; (d) Rio Solis bridge (Uruguay), determination of optimum locations to drill holes in beam; (e) Luján Cathedral, studies of ornaments; (f) Ushuaia harbour, observation of cracks in underwater sections of pillars after a ship collision